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PRELIMINARY STUDY OF APPLIED LOAD FACTORS IN BUMPY AIR

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Summary

The object of this note is to present the results, obtained to date by the National Advisory Committee for Aeronautics, of a study of accelerations or applied load factors experienced by airplanes flying through "rough" or "bumpy" air.

Theoretical relations involved in the study are reviewed to furnish a basis upon which the experimental data can be properly analyzed. The structure of the atmosphere in relation to the load-factor problem is briefly discussed, and the acceleration data obtained on a number of flights with various airplanes are presented and analyzed to the extent that the results are applicable to any airplane.

From the study thus far, it appears that it will be possible to determine the proper design load factors for any airplane in a rational way. However, so little is yet known of the structure of the atmosphere that the specific velocities of air currents indicated by the present data should not be construed as the values to be adopted as a basis for design.

Introduction

As any experienced airplane passenger knows, there are certain conditions under which an airplane is subjected to rather abrupt shocks in the air. These shocks, which are commonly referred to as "bumps," are simply manifestations of more or less abrupt changes in lift caused by changes in angle of attack and relative air speed as the airplane flies through an unsteady atmosphere.

From the standpoint of the structural design of transport or "nonacrobatic" airplanes, which never need be subjected to maneuvers more severe than the very mild turns, etc., required to achieve a given destination, the "bumps" experienced in flying through "rough" air are of considerable importance, since they give rise to the structural loads for which the wings should be designed. In the past, practically no quantitative information on the structure of the atmosphere in its relations to applied loads on the airplane has existed. To supply this deficiency, the National Advisory Committee for Aeronautics is conducting an investigation of the accelerations obtained in flight through rough air on a number of transport airplanes flying regular scheduled trips. To date only a small amount of information has been obtained. However, enough has been accumulated to throw considerable light on the subject of applied load factors in rough air. With the object of presenting this information this note has been prepared.

The theoretical relationships and the structure of the atmosphere are briefly discussed so that the true significance of the acceleration data can be appraised. It is not claimed that the data obtained thus far are sufficiently extensive to furnish a solid foundation for the structural design. It appears, however, that load factors for airplanes of the nonacrobatic class may be determined in a rational way when more extensive statistical information on the structure of the atmosphere is available.

Theoretical Relationships

The airplane is assumed to encounter an air current whose velocity vector is at any angle to the longitudinal axis of the airplane, but in the plane of symmetry. The current, or gust, is assumed to be sharply defined relative to the surrounding atmosphere, or equivalently, it is assumed that there is no angular displacement of the airplane from its initial attitude and no change of velocity relative to the ground up until the time the maximum effect of the "bump" or gust is felt (Figure 1).

The following symbols are used:

α_a = initial angle of attack, measured from zero lift of the airplane before encountering gust.

α_{a_1} = angle of attack immediately after encountering gust

$\Delta\alpha$ = $\alpha_{a_1} - \alpha_a$.

V = relative velocity of airplane with respect to the air corresponding to angle of attack α_a.

V_1 = relative velocity of airplane with respect to the air corresponding to α_{a_1}.

U = velocity of gust relative to the surrounding atmosphere in which the airplane is flying initially.
β = angle between velocity vectors U and V.
θ = angle between velocity vector V and horizontal.
W = weight of airplane.
S = area of lifting surfaces (assumed here as the wing area).
$a = \dfrac{\Delta C_L}{\Delta \alpha}$ = slope of lift curve of wing or wing cellule.
$n = \dfrac{L}{W}$ = applied load factor.
L = lift.

Upon encountering the gust the following lift equation may be written:

$$L_1 = (a\alpha_{a_1}) S \frac{\rho}{2} V_1^2 \tag{1}$$

By the parallelogram law of vectors,

$$V_1 = \sqrt{U^2 + V^2 + 2UV \cos \beta}.$$

Also,

$$\alpha_{a_1} = \alpha_a + \Delta \alpha.$$

Substituting these values of V_1 and α_{a_1} in equation (1), we have,

$$L_1 = a(\alpha_a + \Delta \alpha) S \frac{\rho}{2} (U^2 + V^2 + 2UV \cos \beta) \tag{2}$$

The lift equation which applies for the steady condition of flight prior to encountering the gust is,

$$W \cos \theta = a\alpha_a S \frac{\rho}{2} V^2 \tag{3}$$

Solving equation (3) for the quantity $a\alpha_a S \frac{\rho}{2}$, substituting in equation (2), dividing by W, and simplifying, we have,

$$n = (1 + A^2) \left(\cos \theta + \frac{\frac{\rho}{2} a \Delta \alpha V^2}{\frac{W}{S}}\right) \tag{4}$$

where

$$A^2 = \left(\frac{U}{V}\right)^2 + 2\,\frac{U}{V}\cos\beta$$

and

$$\Delta\alpha = \tan^{-1}\frac{\frac{U}{V}\sin\beta}{1 + \frac{U}{V}\cos\beta} \quad \text{(from Figure 1).}$$

Since β is the angle between U and V, we may differentiate n with respect to β, set the derivative equal to zero, and solve for the angle β at which n is a maximum. This leads to an expression of little practical value; therefore n is plotted against β in Figure 2 for the following two cases:

<u>Case A</u>.- An airplane having a high wing loading and low aspect ratio (or low slope of lift curve).

θ = 0.
ρ = ρ_0 = .002378 slugs per cubic foot.
a = .06 per degree (3.44 per radian).
$\frac{W}{S}$ = 15 pounds per square foot.
V = 150 m.p.h. (220 f.p.s.).
U = 15, 30, and 45 m.p.h.
$\frac{U}{V}$ = .1, .2, and .3.

<u>Case B</u>.- An airplane of low wing loading and high aspect ratio.

θ, ρ, U, and V the same as in Case A.
a = .08 per degree (4.58 per radian).
$\frac{W}{S}$ = 8 pounds per square foot.

Assuming that the wings are not stalled at $\frac{U}{V} = .3$, Figure 2 shows that the load factor is a maximum when β is approximately 80° regardless of the characteristics of the airplane or the relative velocity of the gust. This simply means that the change in angle of attack upon encountering the gust is of much greater importance than the change in air speed.

With β equal to 90°, equation (4) becomes,

$$n = \left[1 + \left(\frac{U}{V}\right)^2\right] \left[\cos\,\theta + \frac{\frac{1}{2}\,\rho\,a\,V^2\,\tan^{-1}\frac{U}{V}}{\frac{W}{S}}\right] \qquad (5).$$

Putting $\left(\frac{U}{V}\right)^2$ equal to zero and $\tan^{-1}\frac{U}{V}$ equal to $\frac{U}{V}$, which substitutions are justified for small values of $\frac{U}{V}$, the expression becomes,

$$n = \cos\,\theta + \frac{\frac{1}{2}\,\rho\,a\,UV}{\left(\frac{W}{S}\right)} \qquad (6),$$

in which U may now be considered the vertical component of the gust.

The last term in the above expression is the increment of load factor experienced upon encountering the gust over and above the initial load factor corresponding to steady flight at the flight-path angle θ. Usually the airplane will be in level flight so that $\cos\,\theta$ will be unity, and any ordinary gliding or climbing angles will not be large enough to cause any appreciable departure from that value. Equation 6, therefore, indicates that the maximum applied load factors experienced in flight through rough air vary lineally with the air speed, the vertical component of the gust, the slope of the lift curve, and inversely with the wing loading. All of these quantities are usually known or can be specified with the exception of the vertical component of the gust, U.

While it is realized that the localized motions of the atmosphere are far more complicated than simple vertical currents, any gust or air current may be considered to have a vertical component which, as the foregoing analysis indicates, is the important element. It is also realized that local air currents may not be sharply defined with respect to the surrounding atmosphere, although there are numerous indications from meteorological sources and from acceleration records taken in rough air that many of them are sharply defined. In fact, an airplane will not feel a "bump" as a distinct shock unless the relative velocity-time gradient of the gust is steep, and it is common experience that the most severe "bumps" are quite abrupt.

For the above reasons, an attempt has been made to collect what information could be found from meteorological sources concerning the intensity of vertical currents in the atmosphere with the hope that some useful data might be obtained. Also, in analyzing the results of acceleration tests made on airplanes in rough air, the data have been inserted in equation (6) and "back-figured" to determine the "effective" values of U which caused the accelerations measured. It is believed that this is the only practicable method of reducing such accelerometer data to a useful form. It is certainly apparent that accelerations, as such, have no significance unless they are considered in the light of the speed, wing loading, and effective aspect ratio of the wing cellule.

In order to test the validity of equation (6) as a good approximation, attempts have been made to discover a "bump" under conditions which would indicate that it would probably remain constant long enough to allow at least two airplanes to fly through it at different speeds. If the accelerations and air speeds obtained on these airplanes when this "bump" was experienced could be inserted in equation (6) and back-figured to obtain approximately the same effective value of U each time, it was felt that the use of the equation would be justified. Such a constant "bump" was found near Langley Field at a low altitude over a stream of water on November 25, 1930.

Two airplanes, a PW-9 pursuit biplane and a Fairchild cabin monoplane whose lift-curve slopes had been measured and which had recording accelerometers and air-speed meters installed in them, were flown over the "bump" several times at different speeds. The following table shows the results obtained.

TABLE I

Run No.	Airplane	$V_{ind.}$ (m.p.h.)	U (f.p.s.)
* 1 a	PW-9	101	11.1
2 a	PW-9	154	11.2
* 1 b	Fairchild	101	10.6
+ 2 b	Fairchild	96	6.7

* Airplanes flown side by side.

+ Airplane about 1/4 mile off course.

Several other runs, subsequent to those given in Table I, were made, but the results indicated that the bump had disappeared or could not be located on these runs. However, in view of the results obtained, it is felt that equation (6) may be used as an approximate expression of the load factors experienced in rough air, or, in other words, that bumps may be assumed as sharply defined.

The Structure of the Atmosphere, with Particular Respect to the Vertical Currents

The structure of the atmosphere is highly complex and localized movements or currents of appreciable intensity are usually present in some form not greatly distant from any given locality. The form and degree of these movements depend in a general way on the season, the latitude, the character of the local topography, and the time of day.

From the point of view of the airplane designer, these currents are of interest only to the extent that they alter more or less suddenly, and/or greatly, the relative velocity and angle of attack of the wing cellule. As has been shown in the preceding section, components of gusts or air currents parallel or transverse to the line of flight have but a small effect upon the wing load, and this effect decreases with increasing speed of flight. With respect to components in the plane of symmetry of the airplane and normal to the direction of flight, the reverse is true. It is therefore justified, for practical purposes, to confine attention to the normal components, and since flight is, in the main, largely a matter of horizontal translation, to confine this attention to vertical currents in the atmosphere.

As far as the relative sharpness of definition of a gust is concerned, this is purely relative and depends not only on the conformation of the gust itself, but upon the speed of the airplane as well. Thus a gust or current which has a velocity gradient from 0 to U over a horizontal distance of 88 feet is experienced as a shock or bump reaching its peak in a half second by an airplane flying into it at 120 miles per hour or 176 feet per second. With higher speed of flight the time is cut down proportionately and the bump becomes more abrupt. So little is known of the structure of the atmosphere that it is almost impossible to say what horizontal velocity gradients may be expected in vertical currents. It is known, however, that convection currents may be quite well defined as is evidenced by the sharp outlines of smoke columns seen on calm days. Further, as any experienced air traveler will attest, abrupt bumps are frequently encountered wherever bumps are found, indicating that the relative gradient is often steep. It seems reasonable, therefore, to consider vertical currents as having infinite velocity gradients, at least until the structure of the atmosphere is better understood. On this premise, then, it is only necessary to establish the magnitude of the vertical velocities of gusts that may be experienced in various conditions of the atmosphere.

In attempting to establish the magnitude of vertical velocities from existing data, it was found that there was a decided lack of information sufficient to be of great statistical value, although some definite values have been gleaned from various sources which, taken as a whole, seem to present a consistent picture.

<u>Line squalls (Reference 1)</u>.- Next to the tornado, which will not be considered here, the line squall is the most violent of atmospheric disturbances. It is caused by the displacement of a mass of relatively still, warm air by a wedge-shaped mass of much colder air advancing, in general, laterally. It may extend over a front ranging up to 1,000 miles and is usually so broad that it is impracticable to fly around it. Because of the large difference in temperature between the advancing cold wedge and the surrounding warm air, violent convection is set up at the front which extends to about 4,000 feet altitude. If accompanied by thunderstorms, as is sometimes the case, strong vertical currents may occur as high as 20,000 feet. In addition to these strong currents at the storm front, strong turbulence exists in the cold air as far back as 5 miles from the front.

No direct measurements of the vertical currents in line squalls have, to the writers' knowledge, been made, but their strength has been deduced from calculations of the velocity necessary to sustain hailstones of various sizes. Since hailstones consist of concentric layers of ice, it has been reasoned that their growth is caused by successive transitions from low to high altitudes in strong convection currents resulting in alternate accumulation of moisture and subsequent freezing. This process takes place until the hailstone becomes of such weight that the vertical currents can no longer give it support, when it falls to the ground. The following table, taken from Reference 1 and due to Dr. G. C. Simpson, gives the velocities necessary to sustain hailstones at an altitude of 13,000 feet (presumably in standard atmosphere). Another column is added to give the "indicated" velocities based on standard sea level density.

TABLE II

Diameter (in.)	True rate of fall (f.p.s.)	"Indicated" rate of fall (f.p.s.)
0.5	53	43
1.0	75	61
1.5	92	76
2.0	106	87
3.0	132	108

Hailstones as large as 0.5 inch in diameter are fairly common. The larger ones are rare, but specimens about 2.5 inches in diameter fell during a thunderstorm at Dallas, Texas, on May 8, 1926.

It is, therefore, seen that vertical currents associated with line squalls may be exceedingly intense. The line squall thus becomes not a problem for the structural designer, but for the weather forecaster associated with air transport operations.

Thunderstorms.- Perhaps equal in intensity to the line squall is the thunderstorm. The same considerations of hailstone formation that apply to line squalls also apply to thunderstorms. In addition, we have an isolated measurement of a vertical velocity in a thunderstorm of 10.5 meters per second (34.4 feet per second) through an altitude of 10,000 feet (Reference 2) and Gregg, in Reference 3, states that vertical velocities in this type of disturbance may be from 8 to 10 meters per second (26 to 33 feet per second). Thunderstorms vary in severity, however, and vertical velocities up to 117 feet per second, as evidenced by the Dallas hailstones, may be expected at times. The same conclusion that applies to line squalls, therefore, also applies to thunderstorms, viz., they must be avoided. Fortunately, the thunderstorm is readily recognized from the air, and being local in character and slow moving can easily be avoided.

Obstructional disturbances.- By obstructional disturbances here are meant any turbulence or gustiness which occurs as a result of winds blowing over obstructions such as buildings, woods, hills, or mountains. Thus, obstructional disturbances may extend only to low altitudes as caused by buildings or low hills, or they may extend to high altitudes as caused by mountains. Gregg (Reference 3) states that the influence of buildings and topographical irregularities extends to about four times the height of the obstruction above the general level of the earth's surface in their vicinity.

There are no direct measurements available of the vertical components of gusts encountered in obstructional disturbances. The acceleration data given in the next section, however, offer some indication of the magnitudes of vertical components to be expected.

Convection currents.- Convection currents are meant here to be the ordinary vertical currents arising as a result of local heating of the terrain. Although the strong vertical currents associated with line squalls and thunderstorms are truly convection currents, it is desirable to classify them separately because of their relative intensity.

Ordinary convection is essentially a fair weather phenomenon and "is most active on summer afternoons, particularly in the vicinity of cumulous clouds." (Gregg) A number of direct observations of the vertical velocities of convection currents have been made at several meteorological stations, all of which are in agreement to the effect that 10 to 13 feet per second are usual average values. Values as high as 23 feet per second have, however, been measured immediately under cumulous clouds (which may always be considered signposts of strong ascending currents).

Presentation of Available Information on Accelerations in Bumpy Air with Particular Reference to Values of U

A few odd bits of information are available concerning the magnitudes of accelerations experienced by airplanes in bumpy air. It has been shown that the magnitude of the acceleration experienced in a bump is of little interest in itself since different accelerations may be experienced by different airplanes encountering the same current, and different accelerations may be experienced by a given airplane in a given current depending upon the speed of flight. Acceleration data obtained in bumpy air are therefore of little value unless accompanied by specific information concerning the aspect ratio of the airplane and the wing loading and speed at the times the accelerations were measured as well as by the correlated meteorological data. In most of the acceleration data which have been obtained, such information is known only approximately because of the lack of appreciation of its importance by those entrusted with the task of sending it with the acceleration records for analysis. However, where specific information is not given, assumptions and deductions can be made from which a fairly good idea of the true meaning of the accelerations can be obtained.

The principal sources of the available information concerning rough-air accelerations are Reference 4, Reference 5, and some recent records obtained by the National Advisory Committee for Aeronautics on airplanes flying on scheduled cross-country trips.

Analysis of Reference 4.- In this paper, which is devoted primarily to a description of the underlying principles of an accelerograph, several records are given which were obtained on scheduled trips of a few European air lines.

Case I

Date: September 9, 1926.
Airplane: "Handley Page Trimotor (O.B.A.HY.)."
Pilot: "Cocquyt."
Route: Brussels to London and return.
Weather: Described as "calm."

Accelerations (in g units)

	Maximum	Minimum	Approximate average
Departing Brussels	1.4	.7	.9 to 1.1
Over Calais Channel	1.0	1.0	1.0
Arrive English Coast	1.3	.7	.8 to 1.2
Between Dover and London	1.6	.55	
Arrive Croydon	1.4	.7	

The description of the airplane was not sufficiently complete to permit assumptions as to wing loading, etc., to be made and hence solutions for U on the basis of equation (6) are not warranted. The data are of interest mainly because of the correlation of specific values of accelerations with what is described as "calm" weather.

Case II

Date: October 11, 1928.
Airplane: Farman "Jabiru" monoplane (F-A.I.C.S.).
Route: Brussels to Le Bourget on the Paris-Amsterdam air line.
Weather (on outbound trip): "Quite disturbed with a 22-kilometers per hour southwest wind at 500 meters altitude and 54-kilometers per hour wind at 1000 meters."
Altitude: "The complete trip was accomplished at low altitude: 100 to 300 meters approximately."

Accelerations (in g units)

	Maximum	Minimum	Approximate average
Brussels "Hal"	1.7	.3	.6 to 1.4
Between Braine-le-Compte and Mons	2.2	.4	.5 to 1.5
Over forest	1.7	0	.6 to 1.4
Between Le Cateau and Bobain	2.3	.3	.6 to 1.4

Weather (return trip): Worse than going trip; 29-kilometers per hour wind at 500 meters.

Note: Records were taken only early in flight on calmer portion of trip. It was the observer's opinion that in later stages of the return trip "very much greater" accelerations were experienced than any on the outbound trip.

Accelerations (in g units)

	Maximum	Minimum	Approximate average
Depart from Le Bourget	2.0	.3	.6 to 1.4

Note: The observer stated that "If consideration is taken of the fact that the aerial lines operate under much more unfavorable winds, these few tests seem to indicate that total vertical accelerations of 2.5 g * * * * must be considerably exceeded at times."

From the remarks on the weather in Case II, above, as well as the statement that the airplane was flown at low altitudes, it seems probable that the sky was overcast with a low ceiling. This would lead to the belief that the bumps encountered were caused by what has been termed "obstructional disturbances" or turbulence in the atmosphere set up by the flow of wind over obstructions on the ground such as hills.

An idea of the magnitudes of the vertical velocities of the air currents encountered by the "Jabiru" in Case II may be obtained by utilizing equation (6) and applying it to the known accelerations and the probable conditions of wing loading and air speed of the airplane. These computations follow:

Characteristics of "Jabiru"*

Span	62.34 ft.	
Total wing area	968.75 sq.ft	
Aspect ratio	$\frac{(62.34)^2}{968.75} = 4$	
Fuel consumption	7,079	lb. gasoline and
	284	" oil in 1,889 miles with six take-offs and landings.
High speed (sea level)	130	mi./hr.
Weights:		
Empty (with equipment)	7,350.2	lb.
Radio	264.6	"
Crew, passengers, and baggage	2,226.6	"
Gasoline	1,463.9	"
Oil	158.7	"
Total	11,464.0	"

Probable Weights as Flown on Paris-Amsterdam Flight

Distance (approximately):	
Paris - Brussels	180 miles
Brussels - Amsterdam	110 "
Total	290 "

Fuel consumption per mile:

$$\frac{7,079 + 284}{1,889} = 3.88 \text{ lb./mi.}$$

*From N.A.C.A. Aircraft Circular No. 15.

Therefore, fuel and oil required for a 300-mile flight equals

$$3.88 \times 300 = 1,164 \text{ lb.}$$

Assuming a 25 per cent margin, the total fuel carried for the complete trip from Paris to Amsterdam (one way) equals

$$1.25 \times 1,164 = 1,450 \text{ lb.}$$

Assuming that the airplane did not carry this quantity of fuel, expecting to refuel at Brussels, the weight of fuel carried would be approximately

$$1.25 (180 \times 3.88) = 873 \text{ lb.}$$

On the basis of the above information and assumptions and further assumptions as to pay load carried, the following table can be made:

Loading		Condition	Weight
Fuel	Passengers		
1,450	2,227	Maximum probable load	11,291
1,450	1,113	Half pay, full fuel	10,178
873	2,227	Full pay, short fuel	10,715
873	1,113	Half pay, short fuel	9,601
873	557	Quarter pay, short fuel	9,045

From this table of weights, assuming a speed of 80 per cent of $V_{max.}$ (.80 x 130 = 104 miles per hour) and a lift-curve slope of 3.8, a table of the probable effective values of U can be made. For this purpose, an acceleration of 2.5 g is assumed, in view of the measurements and observers' remarks, as a representative maximum value to be expected in rough weather on the Paris-Amsterdam route in the "Jabiru" airplane.

Weight	Wing Loading (lb. per sq.ft.)	V (m.p.h.)	Acceleration (g)	U (f.p.s.)
11,291	11.65	104	2.5	25.4
10,178	10.50	104	2.5	22.8
10,715	11.08	104	2.5	24.1
9,601	9.93	104	2.5	21.6
9,045	9.35	104	2.5	20.4

It is thus seen that the effective value of U in Case II for the worst bump lies between a probable minimum of 20 feet per second and a probable maximum of 25 feet per second.

<u>Analysis of Reference 5</u>.-
Airplane: DH-4B.
Pilot: Doolittle.
Route: Between Wilmington and Philadelphia.
Weather: "It is probable that these accelerations are the result of flying into convection currents." Further described as "average rough air."
Altitude: 1,500 feet.
Accelerations: Maximum 2.2 g
Minimum -.5 g

Characteristics of DH-4B

Wing area	440 sq.ft.
Weights:	
Empty	2,939.0 lb.
Fuel	473.5 "
Oil	67.5 "
Armament	356.4 "
Equipment	398.6 "
Crew	360.0 "
Total	4,595.0 "

Solution for U

Assume conditions as follows:
(a) Half fuel, half crew, no armament:

$$\text{Weight} = 4,595 - \frac{473.5}{2} - \frac{360}{2} - 356.4 = 3,822 \text{ lb.}$$

(b) Half fuel, full crew, full armament:

$$\text{Weight} = 4,595 - \frac{473.5}{2} = 4,358 \text{ lb.}$$

Also assume $\frac{\Delta C_L}{\Delta \alpha_{rad.}}$ (a) = 4.0

and $V = .80 \, V_{max.} = 94$ mi./hr.

From equation (6):

$$U_{(a)} = \begin{cases} 15.9 \text{ ft./sec.} \\ -19.8 \text{ ft./sec.} \end{cases}$$

$$U_{(b)} = \begin{cases} 18.1 \text{ ft./sec.} \\ -22.8 \text{ ft./sec.} \end{cases}$$

From these data it may thus be inferred that the effective value of U in "average rough air", caused by ordinary convection currents is in the neighborhood of 16 to 23 feet per second. It is of interest to note the general agreement between these values and those obtained by direct measurement of convection currents given in the preceding section, remembering that the direct measurements refer to average velocities throughout the ascending currents.

N.A.C.A. Data

The data obtained by the National Advisory Committee for Aeronautics are tabulated in Table III (see Figure 3). It is not possible to draw final conclusions from these data because of their meagerness and the lack of specific information concerning the air speed and weather conditions or local topography at the time the worst bumps were experienced. Several facts, however, seem clear. The highest accelerations were obtained over rough country when there were relative strong winds blowing. These accelerations were therefore probably associated with "obstructional disturbances," and the corresponding values of U range up to about 22 feet per second. The lower accelerations, with corresponding values of U up to about 15 f.p.s., were usually not associated with high winds and may have resulted either from convection currents or "obstructional disturbances." Night flights were generally very smooth.

From information that the Committee has received the accelerations of the order of four (4 g) have been obtained in rough air, and it is evident, therefore, that the data of Table III do not represent the worst conditions sometimes encountered, since in no case given in the table did a pilot report unusual conditions.

Resume and Discussion of the Applicability of the Data

The load factor which any airplane will experience upon encountering a vertical current of any degree of intensity can be calculated with fair approximation from the expression,

$$n = \cos\theta + \frac{\frac{1}{2}\rho_o\, a\, U_i\, V_i}{b}$$

where
n = load factor.
θ = flight path angle (to be considered 0).
ρ_o = standard sea-level air density.
a = $\Delta C_L/\Delta \alpha$ radian.
U_i = indicated effective vertical velocity of air current (feet per second).
V_i = indicated air speed of airplane (feet per second).
b = wing loading (pounds per square foot).

All of the quantities involved with the exception of U_i are usually known. Probable values of U_i, based on the accelerometer and meteorological data discussed in the foregoing sections, can be summarized as in Table IV.

TABLE IV

Velocities of Ascending Currents

	Line squalls	Thunder-storms	Obstructional disturbances	Convection currents
U (f.p.s.)	43 to 108	43 to 108	Up to 27 or more	Up to 22 or more
Altitude	Up to 4,000 ft.	Up to 20,000 ft.	Varies with terrain	Up to 4,000 ft.

With respect to the last two columns in this table, there seems to be a good probability that values in excess of those given occur at times, although rather infrequently. Far more data than are now available will be required before any definite values of U for which to design can be established and before the relative frequencies of values of U of different magnitudes can be determined.

In view of the approximate character of the data on U, it is needless to attempt great precision in applying the "bump" formula. Thus, the slope of the lift curve, $\Delta C_L/\Delta \alpha$, need be only approximately determined. Average or probable values for biplanes and for monoplanes are the only ones that should be used at present. These values may be taken as,

a_b = 4.0 per radian for biplanes.

a_m = 4.5 per radian for monoplanes.

The "bump" formula may be represented in chart form, for convenience, as in Figures 4 and 5. In using these charts, read up from the speed scale to the line representing the desired value of U, thence to the left to the line representing the given wing loading, and thence diagonally upward to the load factor scale.

To determine the design conditions, the frequency of occurrence of bumps of various magnitudes should be taken into account. As an illustration of the procedure, let us assume a hypothetical example for an airplane having a gross wing loading of 15.

First, construct a load-factor chart for the given wing loading such as Figure 6. This is done by plotting the general expression for load factor,

$$\frac{L}{W} = n = \frac{C_L(\frac{1}{2}\rho_o V_i{}^2)}{(\frac{W}{S})}$$

which is simply a form of the general lift equation, with the symbols having their usual or standard significance. Now let us assume that the airplane is a monoplane having an estimated high speed of 160 miles per hour and a cruising speed of 135 miles per hour. Also, let us assume that the pilot is obliged by mandatory requirements not to exceed 15 per cent in excess of the high speed or 185 miles per hour. So much for the performance of the airplane. Now let us say that a vertical velocity in gusts equal to 15 feet per second occurs with sufficient frequency so that the airplane may be expected to encounter this current at any speed up to the limiting speed of 185 miles per hour. Also, let us say that more severe bumps, with U = 25 feet per second, may be encountered, but that they are so infrequent that they may be assumed to occur only at the most common flying speeds, namely, cruising speed or less.

On this basis the dotted boundary line on the load factor chart of Figure 6 may be determined by means of the "bump" formula or chart. The area enclosed by this dotted line represents all of the probable conditions which are likely to be encountered in flight on the basis of our original assumptions. Points A, B, C, and D will usually be found to be the critical conditions, although not necessarily so. Note that points A and B are "high angle of attack" and "low angle of attack" conditions, respectively, and that there are two critical inverted flight conditions, one of them near zero lift. If a factor of safety of 2 is applied to give the design load factors, the boundary line is expanded to give the dot-dash line shown.

Recommendations

1. Measurements of accelerations in rough air should be continued until a sufficient quantity of data are obtained to be of statistical value.

2. It is highly desirable that closer liaison be effected between those agencies obtaining these data and those analyzing them to the end that better correlation between the accelerations and the corresponding conditions of weather, terrain, etc., can be had.

3. A combined air-speed meter and accelerometer, which would require no attention in service, should be devised so that exact relationships between the speeds and accelerations can be established over a long period of operation on any airplane.

4. Attempts should be made to determine velocity gradients through cross sections of vertical currents so that proper allowance for the vertical velocity of the airplane in the current can be made. In other words, the validity of the "bump" formula should be further verified.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 9, 1931.

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TABLE III. N.A.C.A. Accelerometer Measurements in Rough Air

Record No.	Route	Airplane	Date of flight	Time of flight	* $\frac{W}{S}$	** V_i (mph) f.p.s.	Max. and Min. accel. ("g")	*** "U" ind. f.p.s.	Av. altitude maintained	Weather	Pilot's comments
1	Salt Lake Cheyenne	221†	9-11-30	3:35 P.M. 6:20 P.M.	12.7	(125) 183	1.6 .3	8.5 -10.0	---	Clear	---
2	Oakland Sacramento	221	9-10-30	8:00 A.M. 8:41 A.M.	10.6	(120) 176	1.6 .4	7.4 -7.4	2000	Good	Very smooth flight.
3a	Sacramento Reno	221	9-10-30	4:57 P.M. 5:47 P.M.	10.6	(120) 176	1.3 .6	3.7 -4.9	13500	Heavy clouds over mountains	Flew above clouds except for occasional heads.
3b							1.8 -.4	9.9 -17.3			Very rough descending through clouds above Reno.
4	Seattle Portland	221	9- 9-30	8:45 A.M. 9:53 A.M.	10.6	(125) 183	1.5 .5	5.9 -5.9	3000	Heavy clouds - broken mostly below 3000 ft.	Very smooth flight.

Remarks

1 Average accelerations about same as maximum throughout flight.
2 Several local bumps recorded 15 minutes after take-off.
3a Average accelerations less than maximum.
3b Record shows high accelerations during last 5 minutes before landing; undoubtedly these occurred while descending through clouds.
4 Record shows only occasional bumps.

(All references listed at end of table.)

TABLE III. N.A.C.A. Accelerometer Measurements in Rough Air (Cont'd)

Record No.	Route	Airplane	Date of flight	Time of flight	* $\frac{W}{S}$	** V_i (mph) f.p.s.	Max. and Min. Accel. ("g")	*** "U" ind. f.p.s.	Av. altitude maintained	Weather	Pilot's comments
5	Portland Medford	221	9- 9-30	10:24 A.M. 12:10 P.M.	10.6	(125) 183	1.8 -.2	9.5 -14.2	6000	Approx. same as No. 4 except clouds higher. Latter part, rain squalls. Rain at Medford.	Rougher than No. 4. Shortly after 11:00 A.M. one bump caused passengers to leave their seats.
6	Medford Oakland	221	9- 9-30	1:25 P.M. 4:00 P.M.	10.6	(125) 183	1.9 .1	10.7 -10.7	6000	Improved toward Oakland.	Worst bumps experienced upon approaching Oakland.
10	Cheyenne Salt Lake	‡‡ 276	9-12-30	8:09 A.M. 12:58 P.M.	9.4	(100) 147	2.65 -.3	22.7 -17.9	11500 and 7600	Favorable. High cirro-stratus. Wind S.W. 35 m.p.h.	Worst bumps encountered between Elk Mt. and McFadden.
11a	Salt Lake Reno	276	9-12-30	12:52 P.M. 4:50 P.M.	8.4	(100) 147	2.35 -.6	16.6 -19.7	6000	Cloudy. Wind S.W. 15 m.p.h. at ground, 45 m.p.h. at altitude.	Worst bumps experienced upon crossing ranges.

Remarks

5 Negative load factor of -.2 is one mentioned by pilot. Numerous bumps recorded within range of +.2 & +1.8.

6 Worst bump recorded at 2:07 P.M.; near Oakland accel. became frequent, ranging from .2 to 1.8 g.

10 Max. accel. usually gave load factors ranging from -.05 to 2.1, which would give values of "U" of -14.5 and +15.1 f.p.s., respectively.

11a Record shows that worst bumps occurred when crossing mountain ranges both approaching and leaving Elko. Load factors experienced approx. same in each case.

TABLE III. N.A.C.A. Accelerometer Measurements in Rough Air (Cont'd)

Record No.	Route	Airplane	Date of flight	Time of flight	* $\frac{W}{S}$	** V_i (mph) f.p.s.	Max. and Min. accel. ("g")	*** "U"$_{ind.}$ f.p.s.	Av. altitude maintained	Weather	Pilot's comments
11b							2.65 -.65	20.3 -20.3			
12	Reno Oakland	276	9-12-30	5:00 P.M. 7:00 P.M.	8.4	(100) 147	2.2 .1	14.8 -11.1	5000	Overcast, with storm approaching from N.W. Clouds high, thin and broken	Worst bumps encountered between Reno and Summit, over the Concord Hills.
13	Cheyenne Salt Lake	276	12-29-30	A.M.	9.7	(100) 147	2.15 -.35	16.3 -19.2			
14	Salt Lake Reno	276	12-29-30	P.M.	9.7	(100) 147	2.00 -.20	14.2 -17.1			
15	Cheyenne Salt Lake	276	1- 4-31	5:31 A.M. 8:10 A.M.	9.7	(100) 147	1.35 .50	5.0 -7.1			
16	Salt Lake Reno	276	1- 4-31	8:25 A.M. 12:40 P.M.	8.8	(100) 147	1.35 .50	4.5 -6.4			

R e m a r k s

11b	Record shows maximum acceleration experienced while approaching Reno from the east.
12	Record shows worst bumps occurred 12 minutes after taking off from Reno.
13	Pilot made no report of weather. Record indicates generally rough air. Negative load factors were experienced three times.
14	Pilot made no report. Record similar to No. 13.
15	Pilot made no report. Record shows continuous bumps of same magnitude.
16	Pilot made no report. Record similar to No. 15.

TABLE III: N.A.C.A. Accelerometer Measurements in Rough Air (Cont'd)

Record No.	Route	Airplane	Date of flight	Time of flight	* W/S	** V_i (mph) f.p.s.	Max. and Min. accel. ("g")	*** "U" ind. f.p.s.	Av. altitude maintained	Weather	Pilot's comments
17	Reno Oakland	276	1- 4-31	2:12 P.M. 4:12 P.M.	8.8	(100) 147	1.80 -.50	10.3 -19.4	10000	Good. No clouds. N.W. wind.	Worst bumps around Verdi.
18	Oakland Reno	276	1- 9-31	8:00 A.M. 9:57 A.M.	8.3	(100) 147	1.45 .22	5.5 -9.5	6000	Clear, with some light ground fog. Low fog in mountains. Wind N.E. 10 m.p.h.	Generally bumpy; worst bumps encountered over the Concord Hills, between Auburn and Summit.
19	Reno Salt Lake	276	1- 9-31	10:30 A.M. 2:20 P.M.	8.2	(100) 147	1.70 .17	8.4 -10.0			
20	Salt Lake Cheyenne	276	1-13-31	4:00 P.M. 7:04 P.M.	9.4	(100) 147	1.53 .15	7.3 -11.7			
21	Salt Lake Reno	††† 7137	1-30-31	9:37 A.M. 1:45 P.M.	10.0	(100) 147	1.1 .9	1.4 -1.4	10000	Clear to broken overcast. Cirrus clouds.	Worst bumps encountered over Ruby Mountains.

Remarks

17 Record shows two local areas where bumps occurred, at 3:13 and 3:37 P.M.
18 Record shows generally rough air with a few isolated maximum accelerations.
19 Pilot made no report. Record indicates generally rough air. Very similar to No. 18.
20 Pilot made no report. Records indicate relatively smooth air. Average load factors .5 to 1.35 corresponding to values of "U" of -6.9 and +4.8.
21 Relatively smooth as judged by record.

TABLE III. N.A.C.A. Accelerometer Measurements in Rough Air (Cont'd)

Record No.	Route	Airplane	Date of flight	Time of flight	* $\frac{W}{S}$	** V_1 (mph) f.p.s.	Max. and Min. accel. ("g")	*** "U" ind. f.p.s.	Av. altitude maintained	Weather	Pilot's comments
22	Reno Oakland	7137	1-30-31	2:30 P.M. 4:35 P.M.	10.2	(120) 176	1.5 .35	6.1 -7.9	2000	Partly cloudy with showers.	Practically calm. Worst bumps encountered over Mt. Diablo approximately 15 miles out of Oakland.
23	Oakland Reno	7137	2- 6-31	8:00 P.M. 10:40 P.M.	10.2	(120) 176	1.25 .60	3.0 -4.9	5000	Storm west end clear east.	Practically calm. Very few bumps, if any.
24	Reno Cheyenne	7137	2- 7-31	10:15 A.M. 8:00 P.M.	9.8	(105) 154	1.35 .50	4.7 -6.7	8000	Fog at Elko and Salt Lake. Light N.W. wind.	
25	Cheyenne Salt Lake	7137	2- 8-31	10:20 A.M. 3:00 P.M.	10.8	(110) 161	1.45 .55	6.3 -6.3	8000	Clear on run, solid overcast at Salt Lake about 2000 ft. thick.	Nearly calm but bumpy between Laramie and Ft. Steel.
26	Cheyenne Salt Lake	7137	2-13-31	7:46 P.M. 12:25 A.M.	11.1	(100) 147	1.15 .80	2.4 -3.2	8000	Light fog at Cheyenne. Light haze and smooth at Salt Lake.	Worst bumps at Elk Mountain and Wasatch Mountains.

R e m a r k s

22 Relatively smooth as judged by record except during last 15 minutes before landing at Oakland.
23 Records show a few bumps on west end. Night flight.
24 Bumpy upon approaching and leaving Elko.
25 Records show bumps as in pilot's comments but also equally severe ones upon approaching and leaving Rock Springs.
26 Flight made at night. Record shows that it was relatively smooth.

TABLE III. N.A.C.A. Accelerometer Measurements in Rough Air (Cont'd)

Record No.	Route	Airplane	Date of flight	Time of flight	* W/S	** V_i (mph) f.p.s.	Max. and Min. accel. ("g")	*** "U" ind. f.p.s.	Av. altitude maintained	Weather	Pilot's comments
27	Salt Lake Reno	7137	2-14-31	1:35 A.M. 6:05 A.M.	10.2	(100) 147	1.15 .80	2.2 -2.9	7000	Good. No clouds. S.S.W. wind 10 m.p.h.	
28	Reno Salt Lake	7137	2-14-31	7:14 A.M. 11:33 A.M.	10.0	(100) 147	1.10 .80	1.4 -2.9	8500	Cloudy and foggy with storm clouds. S.W. wind 15 m.p.h.	Worst bumps near Reno.
29	Salt Lake Wendover	7137	2-14-31	10:30 P.M. 12:05 A.M.	10.0	(100) 147	1.10 1.0	1.4 0			
30	Wendover Wendover	7137	2-15-31	6:40 A.M. 7:45 A.M.	10.0	(100) 147	1.30 1.00	4.3 0			
31	Wendover Reno	7137	2-15-31	12:06 P.M. 4:02 P.M.	10.0	(100) 147	1.75 .45	10.7 -7.9	7000	Fog. S.W. wind 15 m.p.h. at altitude.	Worst bumps encountered upon approaching mountains.
32	Reno Salt Lake	7137	2-16-31	12:00 P.M. 6:53 A.M.	9.6	(100) 147	1.10 .90	1.4 -1.4	7000	Fog. Alto-cumulus clouds encountered. N. wind 10 m.p.h. at altitude.	Very calm.

Remarks

27 Flight made at night and load factors recorded were low.
28 Maximum bumps experienced during first 15 minutes after leaving Reno.
29 Pilot made no comments. Flight made at night and record indicates that it was smooth.
30 Pilot made no comments except that he returned to Wendover on account of the weather.
31 Records indicate that worst bumps were experienced upon leaving Elko.
32 Flight made at night. Record indicates that it was very smooth.

TABLE III. N.A.C.A. Accelerometer Measurements in Rough Air (Cont'd)

Record No.	Route	Airplane	Date of flight	Time of flight	* W/S	** V_i (mph) f.p.s.	Max. and Min. accel. ("g")	*** "U" ind. f.p.s.	Av. altitude maintained	Weather	Pilot's comments
33	Oakland Reno	7137	2-19-31	8:00 P.M. 11:20 P.M.	10.3	(90) 132	1.50 .25	8.2 -12.3	6000	Clear with 48 m.p.h. N.E. wind.	Worst bumps between Blue Canyon and Truckee.
34	Reno Salt Lake	7137	2-19-31	11:35 A.M. 5:35 P.M.	10.2	(100) 147	1.80 .50	11.6 -7.3	7000	Few scattered clouds 15 m.p.h. N.N.E. wind.	
35	Salt Lake Reno	7137	2-20-31	7:00 A.M. 11:30 A.M.	9.9	(110) 161	1.50 .35	6.4 -8.4	6000	Broken and overcast with cumulus clouds.	
36	Reno Oakland	7137	2-20-31	11:38 A.M. 1:18 P.M.	9.8	(110) 161	1.30 .45	3.8 -7.0	5500	Clear N. wind at 25 m.p.h.	Rough all the way but worst around Snow Mountain.
37	Oakland Reno	7137	2-20-31	8:35 P.M. 12:32 A.M.	10.7	(120) 176	1.25 .65	3.2 -4.5	11000	N.E. wind 50 m.p.h.	Worst bumps 25 miles west of Reno.
38	Reno Salt Lake	7137	2-21-31	12:47 A.M. 5:35 A.M.	9.6	(100) 147	1.40 .65	5.5 -4.8	6000	Clear. 25 m.p.h. N.E. wind.	Worst bumps just out of Reno and over Great Salt Lake.
39	Salt Lake Reno	7137	2-22-31	9:33 P.M. 1:55 A.M.	10.1	(100) 147	1.0 1.0	0 0	8000	Clear and calm, with light N.E. wind.	

R e m a r k s

33 Records show maximum load factors were recorded a number of times from 10:20 to 10:45 P.M. Night flight.
34 Generally smooth but local bumps encountered at times.
35 Bumpy upon approaching and leaving Elko.
36 Records indicate that it was rough all the way from Sacramento to Oakland. Load factor ranged from .45-1.30.
37 Relatively smooth. A few local bumps. Night flight.
38 Night flight.
39 Flight made at night. No noticeable bumps.

TABLE III. N.A.C.A. Accelerometer Measurements in Rough Air (Cont'd)

Record No.	Route	Airplane	Date of flight	Time of flight	* W/S	** V_i (mph) f.p.s.	Max. and Min. accel. ("g")	*** "U" ind. f.p.s.	Av. altitude maintained	Weather	Pilot's comments
40	Reno Oakland	7137	2-23-31	2:08 A.M. 5:17 A.M.	10.1	(120) 176	1.0 1.0	0 0	10000	Foggy in bay region. Wind S.W. 5 m.p.h.	No bumps encountered.
41	Oakland Salt Lake	7137	2-24-31	8:00 P.M. 2:05 A.M.	10.0	(100) 147	1.0 1.0	0 0	7000	Clear	No bumps encountered.
42	Cheyenne Salt Lake	276	2-24-31	5:28 A.M. 9:40 A.M.	9.6	(100) 147	1.3 .4	4.2 -8.4			
43	Salt Lake Reno	276	2-24-31	9:00 A.M. 12:45 P.M.	8.8	(100) 147	1.60 .25	6.5 -9.7			
44	Reno Oakland	276	2-24-31	12:58 P.M. 2:40 P.M.	8.8	(100) 147	1.45 .25	5.8 -9.7	7000	Clear. Wind N.E. 14 m.p.h. at altitude. N.W. in Sacramento Valley at ground.	Generally rough all the way. Semi-severe bumps at Sierra Summit and San Francisco Bay area.
45	Salt Lake Reno	7137	2-26-31	11:14 P.M. 3:45 A.M.	9.5	(100) 147	1.0 1.0	0 0	9000	Clear. Wind W.N.W. 10 to 30 m.p.h.	No bumps.

Remarks

40	Night flight. Record very smooth.
41	Night flight. Record very smooth.
42	Pilot made no report. Record shows generally rough air.
43	Pilot made no report. Record similar to No. 42.
44	------
45	Night flight. Record very smooth.

TABLE III. N.A.C.A. Accelerometer Measurements in Rough Air (Cont'd)

Record No.	Route	Airplane	Date of flight	Time of flight	* $\frac{W}{S}$	** V_i (mph) f.p.s.	Max. and Min. accel. ("g")	*** "U" ind. f.p.s.	Av. altitude maintained	Weather	Pilot's comments
46	Reno Oakland	7137	2-26-31	3:58 A.M. 6:00 A.M.	9.5	(100) 147	1.35 .60	4.8 -5.4	6000	Clear. Wind S.W. 14 m.p.h.	Worst bumps, Reno to Truckee.
47	Oakland Reno	7137	2-28-31	8:00 P.M. 10:10 P.M.	10.3	(120) 176	1.45 .60	5.5 -4.9	--	Clear. Wind east 20 m.p.h.	Bumps encountered last 50 miles.
48	Reno Salt Lake	7137	2-28-31	10:22 P.M. 2:40 A.M.	10.3	(100) 147	1.45 .30	6.6 -10.3	9000	Clear. Wind N. N.E. . 15 m.p.h.	Some roughness at Secret Pass.
49	Salt Lake Reno	7137	3- 1-31	10:58 P.M. 3:09 A.M.	10.3	(100) 147	1.0 1.0	0 0	7000	Clear. N. wind 15 m.p.h.	No bumps encountered.
50	Reno Oakland	7137	3- 1-31	A.M.	10.3	(100) 147	1.0 1.0	0 0	6000	Clear. Wind N.E. 10 m.p.h.	No bumps encountered.
51	Salt Lake Reno	7137	3- 5-31	5:37 A.M. 10:14 A.M.	9.8	(100) 147	1.85 .45	11.9 -7.7			

Remarks

46	Record shows local bumps were encountered 10 minutes after leaving Reno.
47	Record shows worst bumps were encountered midway between Sacramento and Reno.
48	Record shows two local bumps of approximately equal magnitude. Night flight.
49	Night flight. Record very smooth.
50	Record very smooth.
51	Pilot made no report. Maximum load factors recorded on approaching Reno.

TABLE III. N.A.C.A. Accelerometer Measurements in Rough Air (Cont'd)

Record No.	Route	Airplane	Date of flight	Time of flight	* $\frac{W}{S}$	** V_i (mph) f.p.s.	Max. and Min. accel. ("g")	*** "U" ind. f.p.s.	Av. altitude maintained	Weather	Pilot's comments
52	Reno Oakland	7137	3- 5-31	10:22 A.M. 12:07 P.M.	10.0	(120) 176	1.60 .40	7.2 -7.2	1000 to 10000	Clear. Wind N.E. 28 m.p.h.	Bumps encountered 30 miles out of Reno and between Sacramento and Oakland, with worst just before landing at Oakland.
53	Reno Salt Lake	7137	---	---	10.0	(100) 147	1.55 .50	6.4 -7.1	9000	Good. N. wind 15 m.p.h.	No bumps encountered. Some roughness while changing altitude.
54	Anacostia, D.C. Langley Field	†††† O3U-1	1-28-31	11:57 A.M. 1.13 P.M.	11.4	(98) 144	1.52 .53	8.6 -7.8	2000	Clear. Wind 15 m.p.h.	Worst bumps encountered in first third of flight.

R e m a r k s

52 Record shows maximum accelerations when leaving Reno and when approaching Oakland.
53 Record shows a few local bumps.
54 Numerous bumps giving load factors of .5 and 1.5.

R e f e r e n c e s

* Average during flight.
** Average indicated air speed.

$$*** \ "U"_{ind.} = \frac{2\,(n-1)\,\frac{W}{S}}{\rho_0 \ a \ V_i}$$

† Boeing Monomail Model 221; assumed a = 4.1
†† Boeing Mailplane Model 40 B; assumed a = 3.9
††† Boeing Trimotor Model 80; assumed a = 4.0
†††† Vought Corsair; assumed a = 4.0

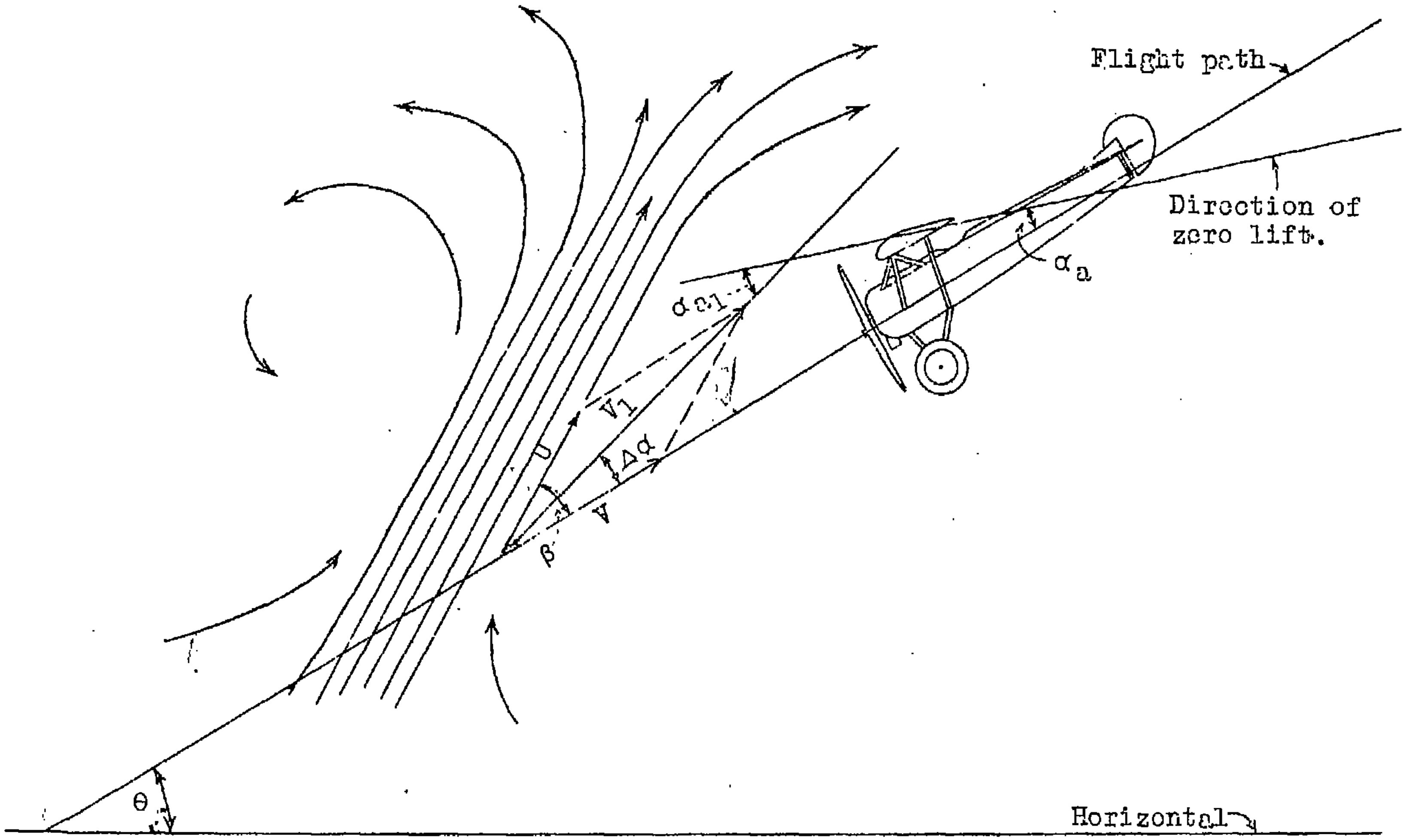

Fig. 1 Airplane encountering gust.

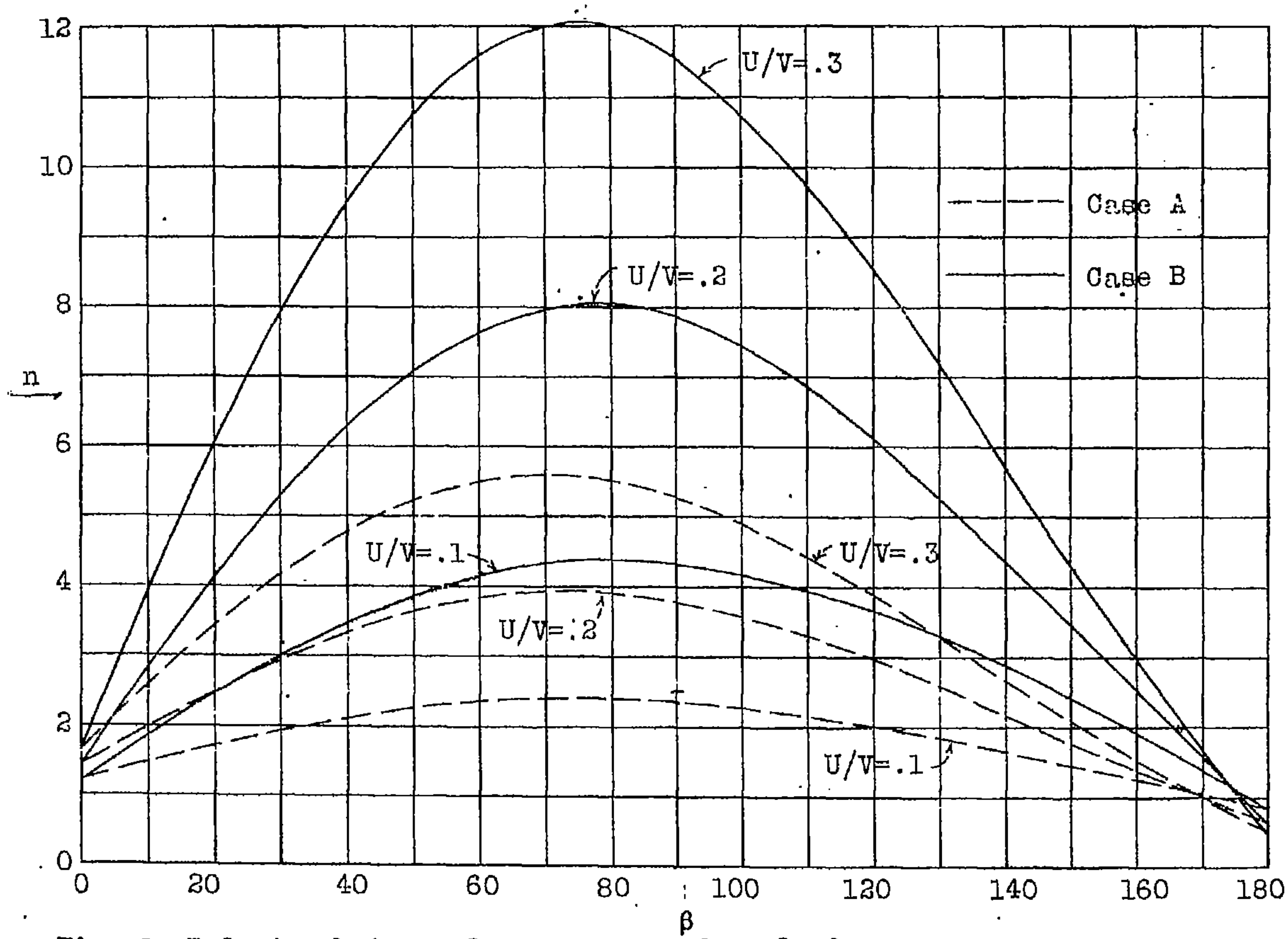

Fig. 2 Relation between load factor and angle β

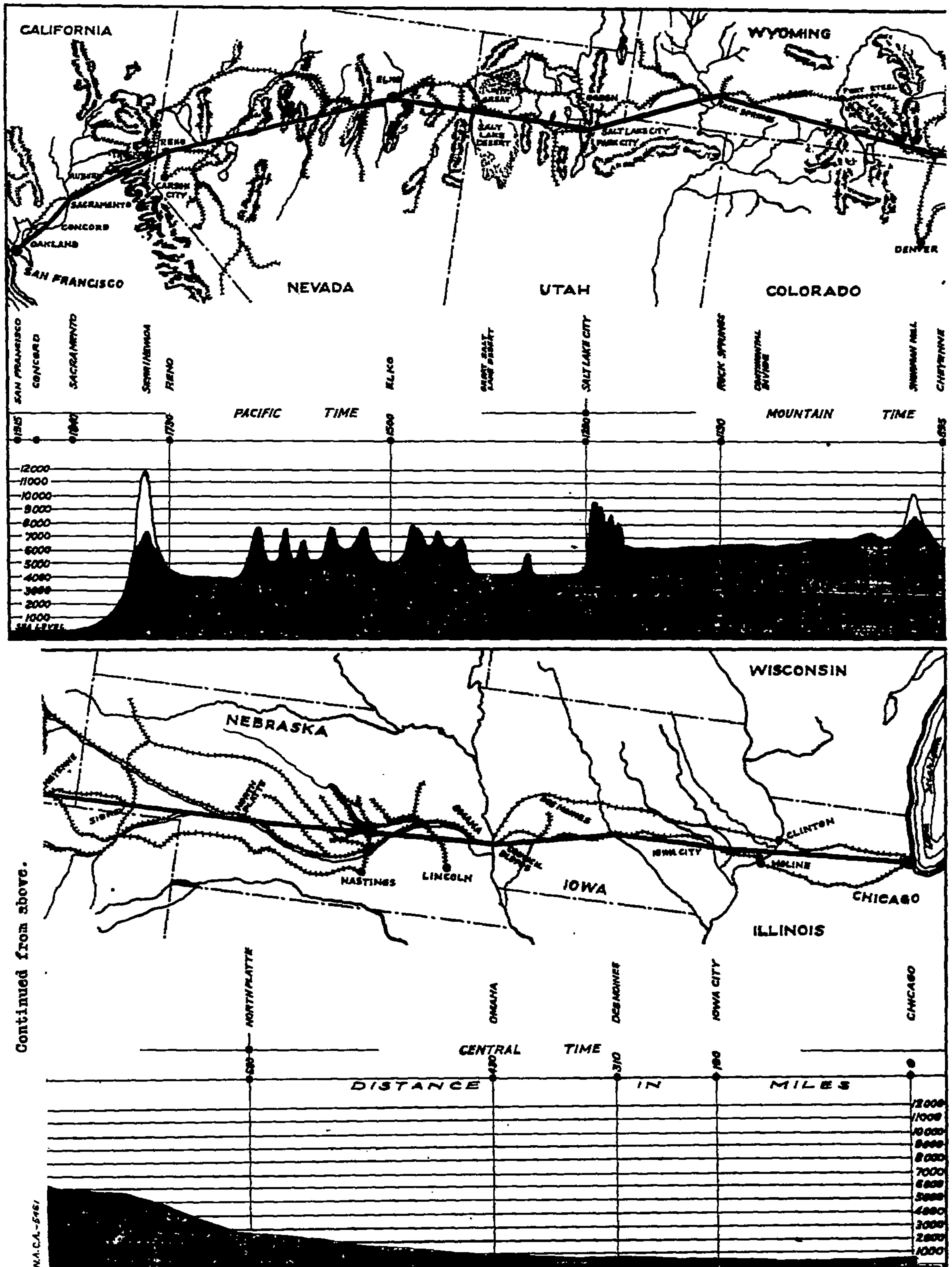

Fig.3 Route over which N.A.C.A. accelerometer measurements were made. (See Table III)

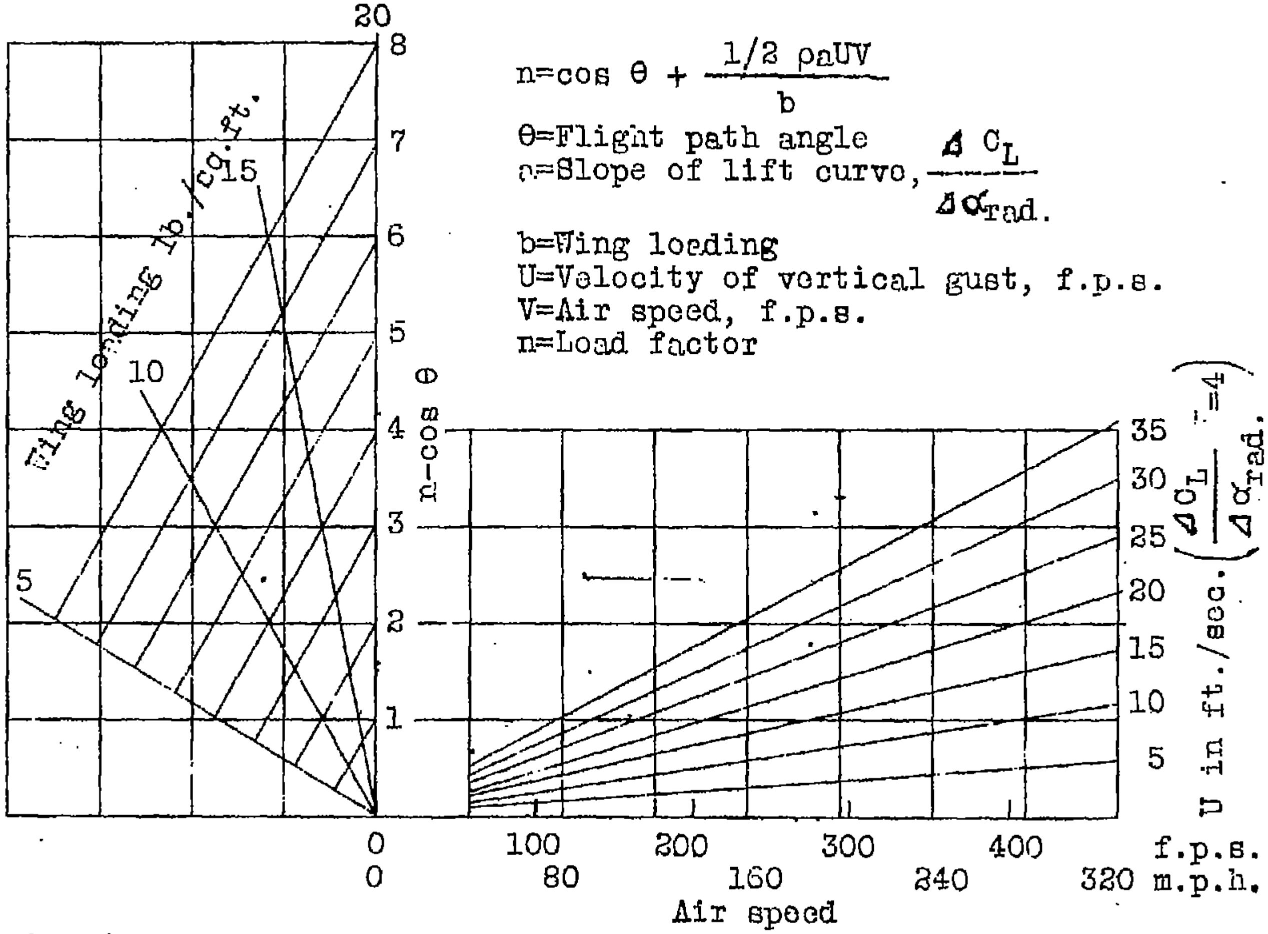

Fig. 4 Applied load factors in bumpy air.
Biplane

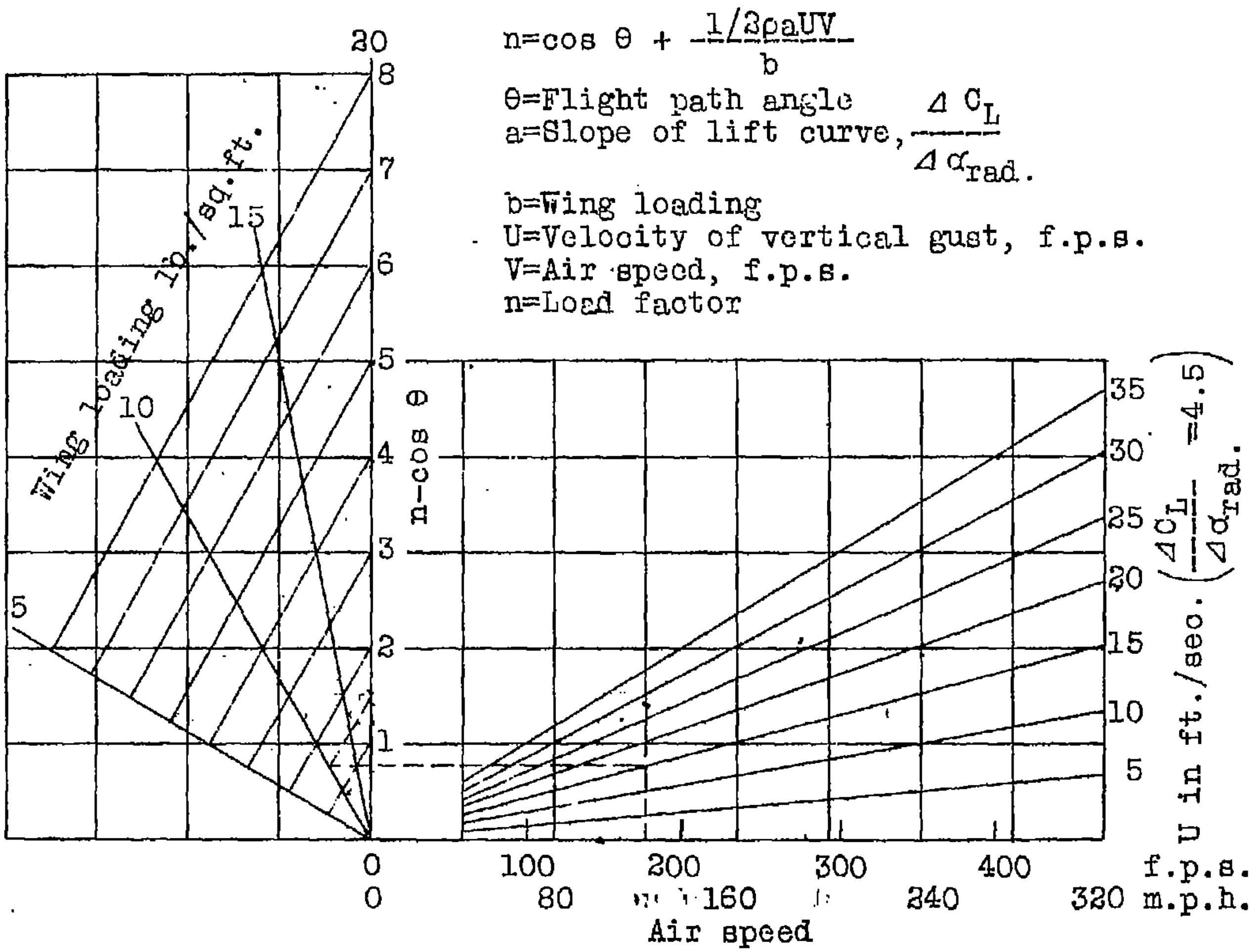

Fig. 5 Applied load factors in bumpy air.
Monoplane

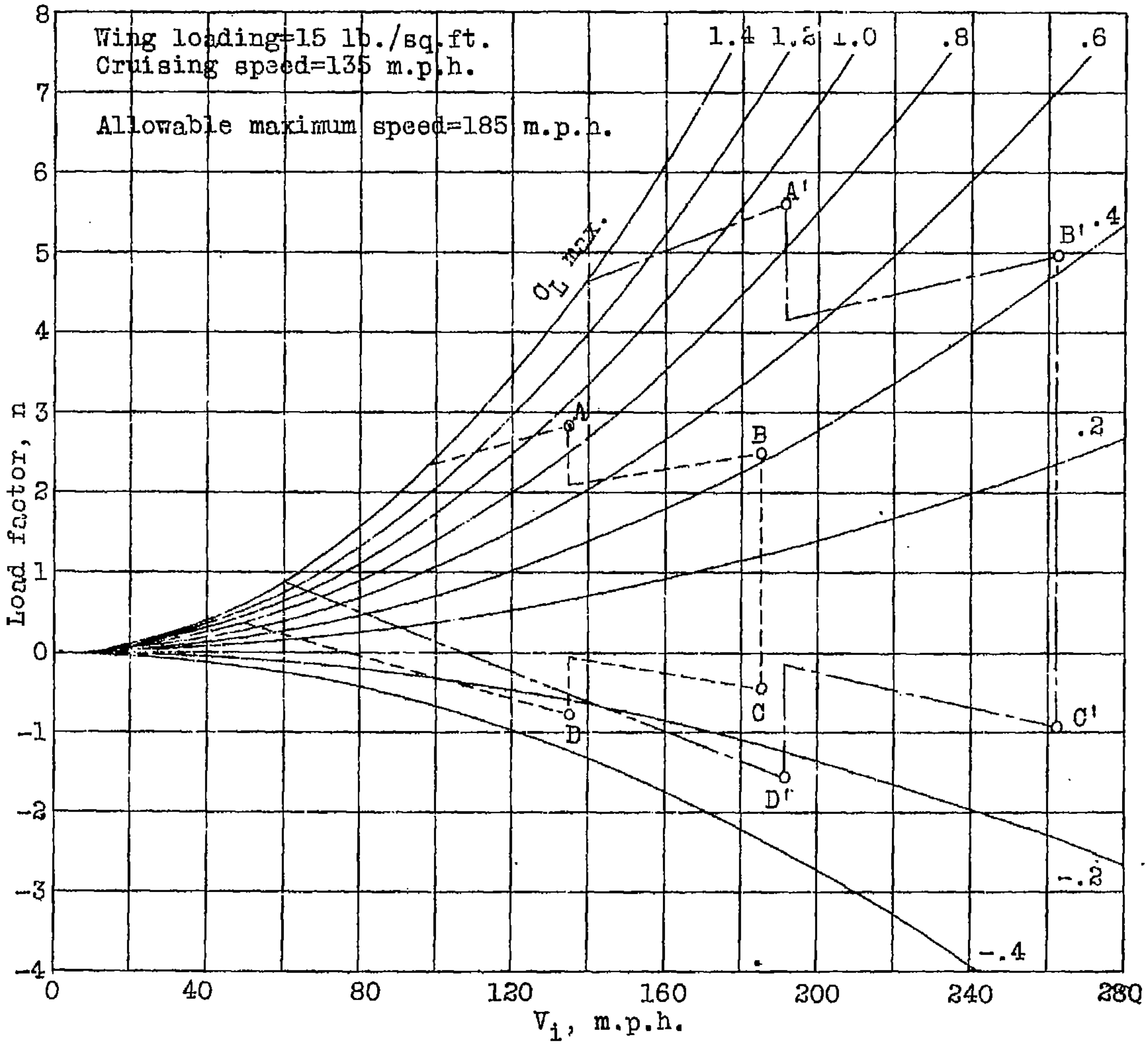

Fig. 6 Load factor chart for a transport airplane.